SMC-TR-93-59

AEROSPACE REPORT NO.
TR-0091(6940-05)-4

Advantages of the LBL 88-inch Cyclotron Ion Beam for SEP Studies

15 September 1993

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THE AEROSPACE CORPORATION
El Segundo, California

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-88-C-0089 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by A. B. Christensen, Principal Director, Space and Environment Technology Center. Capt. Leslie Belsma was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
15 Sept 1993

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Advantages of the LBL 88-inch Cyclotron Ion Beam for SEP Studies

5. FUNDING NUMBERS
F04701-88-C-0089

6. AUTHOR(S)
Koga, Rocky; and Pinkerton, Steven D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Aerospace Corporation
Technology Operations
El Segundo, CA 90245-4691

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-0091(6940-05)-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space and Missile Systems Center
Air Force Materiel Command
2430 E. El Segundo Boulevard
Los Angles Air Force Base, CA 90245

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
SMC-TR-93-59

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The Lawrence Berkeley Laboratory 88-inch cyclotron has been widely used for single-event phenomena (SEP) studies. The advantages and disadvantages of using ions at this facility are compared with those for other accelerator facilities in the US. One major advantage of the 88-inch cyclotron is that several ion species, with varying stopping powers, can be made available in a matter of seconds by simply adjusting the cyclotron frequency. The importance of this capability is illustrated via test results for a high-density SRAM and an EEPROM device type.

14. SUBJECT TERMS
Single-event upset (SEU), Single-event effects (SEE), Latchup, Cyclotron, Accelerator, Lawrence Berkeley Laboratory (LBL)

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

PREFACE

We would like to express our gratitude to W.R. Crain, K.B. Crawford, S.J. Hansel, S.S. Imamoto, D.D. Lau, and R.L. Walter for their assistance in the software development, testing, and analysis of test results.

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I. INTRODUCTION

We have used ions from the Lawrence Berkeley Laboratory (LBL) 88-inch cyclotron as well as from other accelerators to study single-event phenomena (SEP). The advantages and disadvantages of conducting tests at these facilities are compared, taking into consideration: (1) the ease with which the beam intensity and species may be changed; (2) the stopping power and range of available ions; and (3) the cost of operation.

II. CHARACTERISTICS OF THE ION BEAM

A. THE 88-INCH CYCLOTRON

The 88-inch cyclotron has accelerated ion species ranging from protons to heavy ions. In order to achieve high energy without losing high intensity, the accelerator incorporates a sector-focused design.[1]

The resonance conditions for various particles and energies in the 88-inch cyclotron are shown in Figure 1. The resonance frequency is expressed as

$$f = QB / (2\pi M) ,$$

where Q is the charge of the particle, B is the cyclotron pole magnetic field, and M is the mass of the particle. Notice that particles with the same Q/M can be accelerated simultaneously. Since the particle energy is approximately $mv^2/2$, and the frequency, f, is proportional to v, the energy increases nearly as f^2. The energies of accelerated ions, therefore, increase by the square of the charge state.

The upper energy limit for the cyclotron is set by the maximum dee frequency for protons, and by the maximum magnetic field for heavier particles. For low-mass ion species such as protons, the particle revolution frequency equals the dee frequency (the first-harmonic mode of operation). Heavier ions at lower energies are often accelerated using the dee frequency, which is 3 times the particle frequency (the third-harmonic mode of operation). For particles with even lower energies, the fifth harmonic can be used.

B. THE ECR SOURCE

The electron cyclotron resonance (ECR) ion source injects ions into the 88-inch cyclotron.[2] In the source chamber, microwaves heat the plasma electrons, whose motion is governed by the equation,

$$\omega = qB_{Axial} / m ,$$

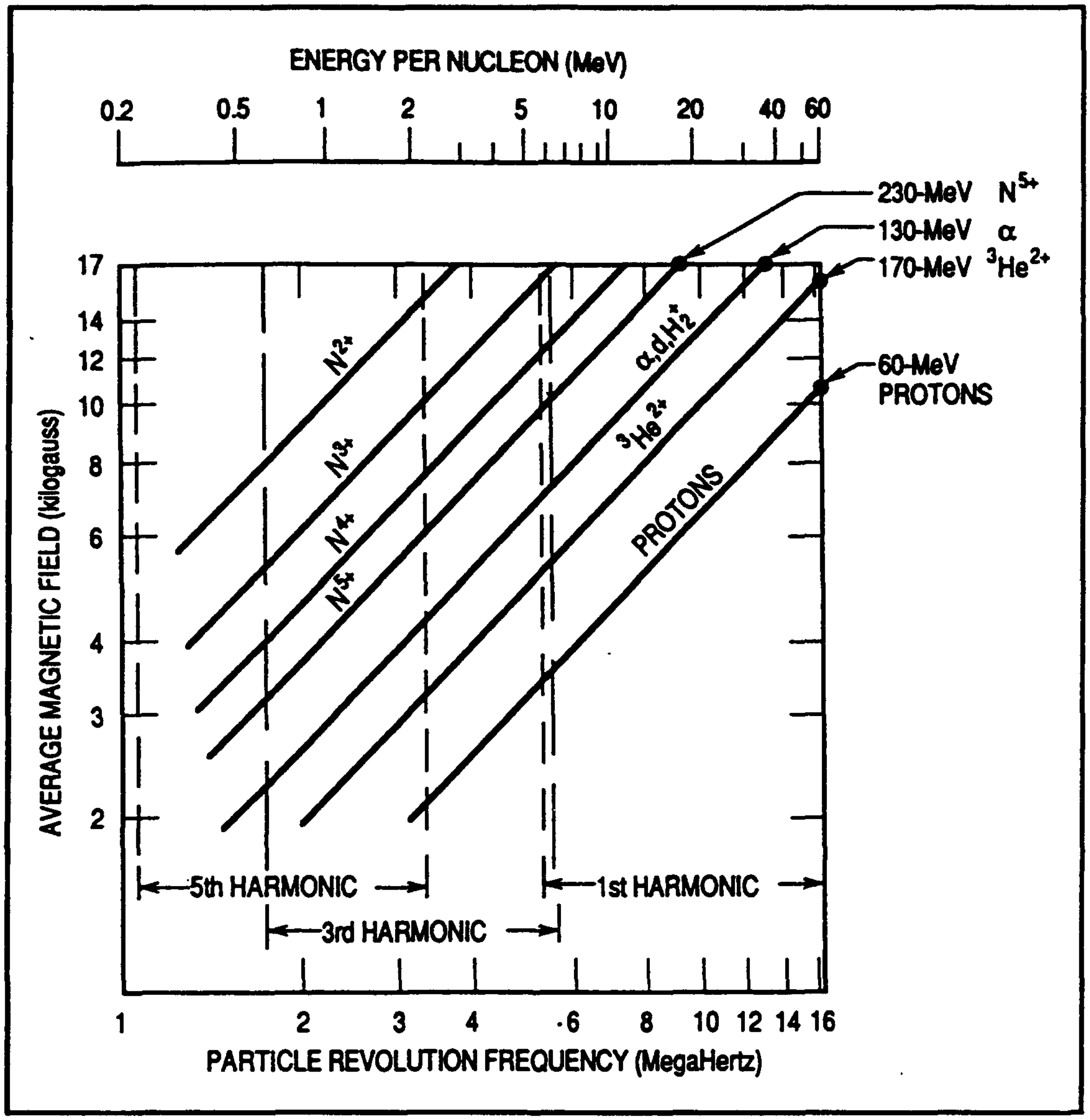

Figure 1. 88-inch cyclotron resonant chart. Operating lines for various particles show magnetic field, frequency, and energy per nucleon.

where ω is the rf frequency, q is the electron charge, m is the electron mass, and B_{Axial} is the resonant magnetic field.[3] The hot electrons strip away ions by sequential, electron-impact ionization, resulting in the production of highly charged positive ions that can be extracted from the source and delivered to the cyclotron for acceleration.

Ions ranging from protons to xenon have been accelerated on a regular, reliable basis. Table 1 lists some of these accelerated beams.

Another characteristic of the ECR source is that the discharge is produced without cathodes so that only the source material injected into the ECR source is consumed (unlike the now-defunct Penning Ion Gauge source at LBL). As a result, the ECR source can be operated continuously for periods as long as several weeks. Also, the recent installation of a wire-mesh ion attenuator at the exit port of the ion source allows the ion intensity to be modified by simply pushing a button on a control panel.[4] Since this operation is carried out prior to the cyclotron acceleration, it has no effect on the accelerator tuning or on the properties of the accelerated particles.

A new ECR ion source installed at the 88-inch facility in 1991 improved the selection of high-energy heavy ions. There are two sources of electrons in the present source chamber — production through the stepwise ionization of atoms and ions, and externally injected plasmas. In the new chamber, an SiO_2 coating on the inside wall enhanced the production of electrons at the wall due to the high secondary-electron emission of this compound. This, in turn, increased the charge state of source ions[5].

C. IMPLICATIONS FOR SEP STUDIES

Ideally, SEP studies should be conducted in a manner that approximates, to the greatest extent possible, conditions encountered in space. Such a test procedure implies the use of the same ion species as those present in the space-radiation environment. The procedure also requires that measurements be performed over a wide energy range for each ion species. Since following such a procedure would be prohibitively expensive, a more practical method, from the point of view of both time and cost, has been used in conducting various tests (the test method has been described in detail elsewhere[6]).

Table 1. Examples of Accelerated Beams (Extracted from Reference 2)

Ion Species	Cyclotron Energy (MeV)	Source Current (eμA)	Cyclotron External (eμA)
$^{14}N^{5+}$	180	63	9
$^{16}O^{5+}$	135	46	4
$^{16}O^{6+}$	315	15	1.1
$^{18}O^{4+}$	117	87	5.5
$^{20}Ne^{6+}$	160	23	2
$^{22}Ne^{5+}$	157	29	3
$^{40}Ar^{9+}$	175	50	2.4
$^{40}Ar^{12+}$	504	6	0.3
$^{86}Kr^{14+}$	301	2.5	0.1
$^{129}Xe^{21+}$	451	0.8	0.03

Our approach is to use several low-energy (in comparison to typical cosmic rays) ions, whose linear energy transfer (LET) values range from a fraction of an MeV/(mg/cm^2) up to 60 MeV/(mg/cm^2). However, to ensure proper assessment of a microcircuit's vulnerability to single-event upset (SEU), a selection of particles with the desired LETs is essential. In this selection, it is absolutely crucial that the particles have sufficient range (and hence energy) to penetrate to the vulnerable region and still produce a significant and determinable amount of charge along the ion track. As a general rule, one should operate on the negative slope portion of the dE/dx vs. E curve, or equivalently, at ion energies in excess of 3 MeV/nucleon. In other words, SEP studies require ions that simulate galactic cosmic rays and trapped protons, with minimal deviations.

It is also very important for SEP testing that only single-species, spatially uniform, mono-energetic ion beams be used.

The combined ECR source and 88-inch cyclotron can provide most of what is needed for SEP studies. Several commonly used ions and their LETs are listed in Table 2.

Table 2. Ions Commonly Used for SEP Study at LBL 88-inch Cyclotron

Ion	Energy (MeV)	LET	Range in Si (μm)
$^{1}H^{1+}$	50	0.01*	>100
$^{4}He^{1+}$	12	0.35	>100
$^{16}O^{7+}$	428	1.0	>100
$^{15}N^{3+}$	67	3.0	>100
$^{20}Ne^{4+}$	90	5.6	55
$^{40}Ar^{8+}$	180	15	48
$^{65}Cu^{13+}$	290	32	45
$^{86}Kr^{17+}$	380	41	45
$^{136}Xe^{27+}$	603	63	47

* LET values given in MeV / (mg/cm^2)

III. ADVANTAGES AND DISADVANTAGES

A summary of the pros and cons of the 88-inch cyclotron as opposed to other accelerators (of similar energies) is provided in Table 3.[7,8]

One large advantage of using the Xe, Kr, Cu, Ar, Ne, and N ion source is that the resonant cyclotron frequencies for these ions are very close to one another. Therefore, they can be tuned essentially simultaneously, and their "optics" can be controlled together. The final separation of ions can be achieved by a slight fine tuning of the main cyclotron frequency. In other words, an "ion cocktail" can be created at the ECR source and accelerated by changing the main frequency slightly. Several "cocktails" of different mixes can be created. However, light ions such as protons and helium must be accelerated separately since their resonant frequencies differ widely from each other.

The production of "ion cocktails" requires the capability to switch ion species with different LETs in and out in a matter of seconds. The Brookhaven National Laboratory (BNL) tandem accelerator uses a sputter-type source[9] since negatively charged ions are needed at the first stage of the tandem accelerator. Sputter-type sources do not commonly produce many different ions at the same time for acceleration. Consequently, it takes several hours to change the accelerated ion species at BNL.

The main disadvantage of the 88-inch cyclotron is that the ion energy cannot be changed gradually. This is not the case at BNL where the energy of ions can be varied continuously. Unfortunately, several hours are required to change the energy.

Another disadvantage of the 88-inch cyclotron is that the maximum proton energy is only 60 MeV. In contrast, 200 MeV protons can readily be accelerated at the Indiana University Cyclotron Facility. In addition, very large accelerators, such as Bevalac, can be used to accelerate ions with energies on the order of 1 GeV. However, an accurate characterization of the beam at such facilities may be difficult to obtain,[10] and the cost of operation is typically very high.

Table 3. Comparison of Accelerators for SEP Study

	LBL 88-inch	Indiana Univ. Cyclotron	BNL Tandem
Light Ions	Yes	Yes	Yes
Heavy Ions	Yes	No	Yes
High LET	Yes	No	Yes
"Ion Cocktail"	Yes	No	No
Max. Proton Energy	60 MeV	200 MeV	30 MeV

IV. BEAM DIAGNOSIS AND DOSIMETRY

Once the beam is extracted to an experimental area, it is important to verify that the beam is suitable for the purpose of the test. Therefore, a beam diagnostic/dosimetry apparatus is used in practically all of the tests. The key elements of the apparatus are as follows:

1. A vacuum chamber capable of maintaining a reasonably good vacuum and providing the capability of easy and rapid sample changes.
2. An accurate, real-time flux monitor.
3. A near-real-time energy and spatial uniformity monitor.
4. A remote-controlled shutter between the flux monitor and sample holder.
5. A mechanized, remote-controlled sample positioning system that moves individual test chips in and out of the beam and changes beam-exposure angles.

The beam diagnostic and dosimetry setup described above has been modified frequently to accommodate varying requirements of SEP tests, and is, of course, not unique. However, it is beyond the scope of this report to discuss the beam diagnostic and dosimetry systems at the various accelerator sites.

V. EXAMPLES OF TEST RESULTS

We will provide two examples of SEP test results that were obtained at the 88-inch cyclotron and illustrate some of the advantages of utilizing this facility.

A. SONY 128K X 8 STATIC RAM (SRAM)

The utility of having "ion cocktails" available is shown in Figure 2, which depicts the SEU and latchup cross-section vs. LET curves for SONY 128K × 8 SRAMs. Since this device type has a rather low LET threshold, various ions with a wide range of LET values were used in this study. Because of this, it was very useful to be able to switch selected ion species in and out during the data collection period. If any other accelerator had been used, we would have had to spend many more hours changing the ion energy/species.

B. SEEQ DM28C256 32K X 8 ELECTRICALLY ERASABLE PROGRAMMABLE ROM (EEPROM)

This device type was tested for SEU first during the read cycle and then again during the write cycle. During the read mode of operation, we obtained the upset cross-section shown in Figure 3. These upsets did not arise from the memory storage section of the device; instead, the upsets were caused at the intermediate latches (these are storage elements) located between the device memory

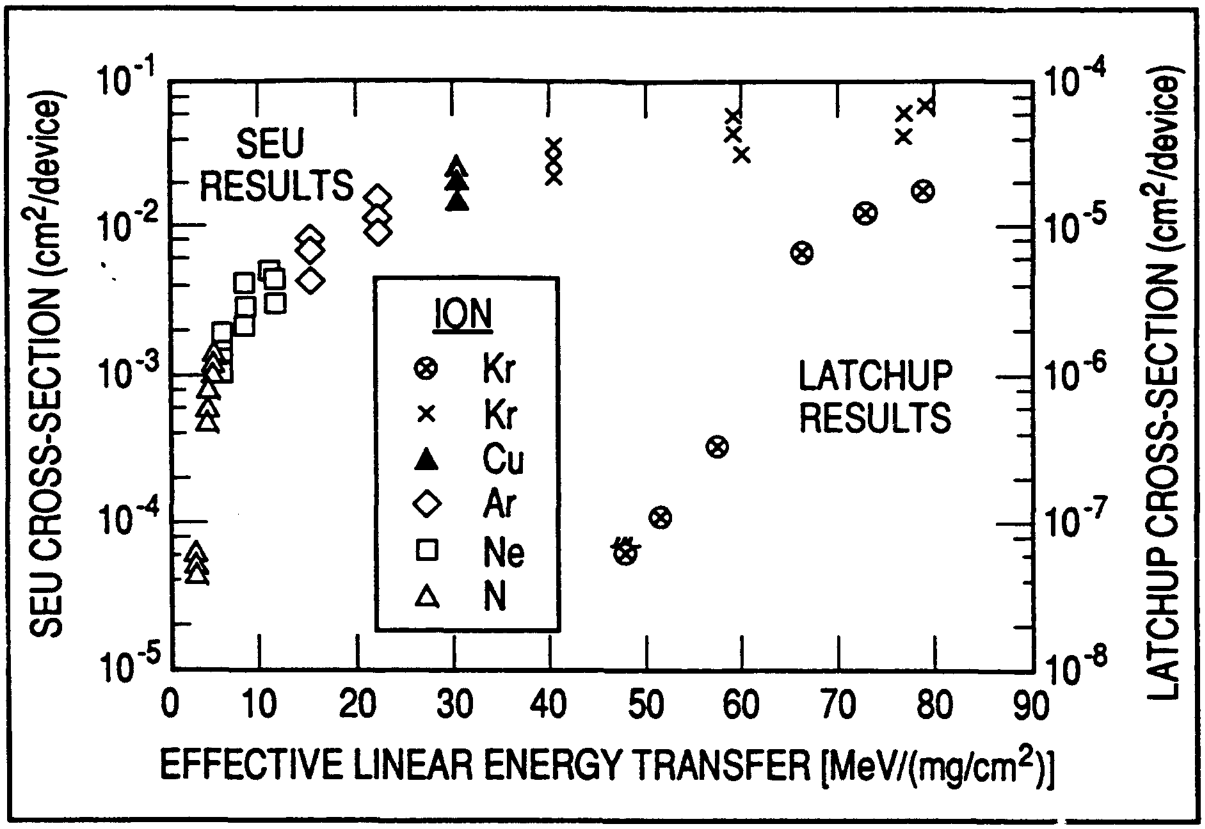

Figure 2. SEU and latchup test results for CXK581000P 1-M Bit SRAM.

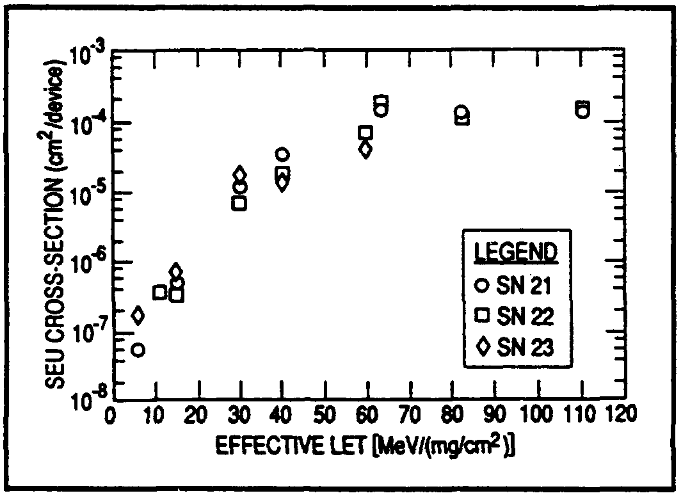

Figure 3. SEU test results for DM28C256 EEPROM (read cycle only).

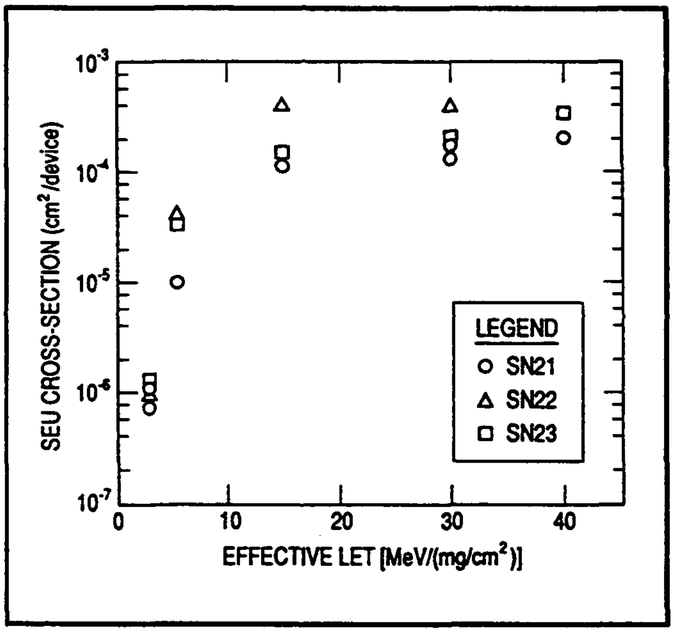

Figure 4. SEU test results for DM28C256 EEPROM (write cycle only).

site and the outputs. During the write cycle, we observed numerous memory errors, as shown in Figure 4. These were upsets in EEPROM memory sites during the write cycle, i.e., incorrect information was being written at memory locations while the device was undergoing irradiation. If the device was written again (without being irradiated with an ion beam), the errors disappeared. Again, the site of upset seemed to have been at the input (intermediate) latches. In other words, upsets that took place in the latches were subsequently transferred to the device memory sites.

In Figures 3 and 4, the cross-section values at the LET of 40 MeV/(mg/cm^2) are about 2×10^{-5} and 2×10^{-4} cm^2/device, respectively. There is, thus, a difference of around one order of magnitude. While taking these data, the beam attenuator described above proved invaluable for making fine adjustments of the intensity.

We also observed permanent errors during the write cycle when irradiating using Cu, Kr, and Xe ion beams. These errors were characterized by an inability to rewrite the correct bit pattern at a memory location. Again, the ability to change ion species quickly was quite helpful.

VI. SUMMARY

Dosimetry of ions at most medium-energy accelerators is relatively straightforward. Hence, one can obtain a uniform, mono-energetic, single-species ion beam at these accelerator sites with relative ease. It is also easy to obtain accelerated ions with sufficient range for SEP study. However, it is difficult to rapidly change the accelerated ion species at most accelerator sites, except at the LBL 88-inch cyclotron, where the species in an "ion cocktail" can be readily changed.

Unfortunately, at the 88-inch cyclotron facility, proton energy is limited to 60 MeV, and a gradual change of ion energies is not possible. Nevertheless, the characterization of the SEP susceptibilities of microcircuits can be still conducted in a cost effective manner at this accelerator site. Combined with the advantages cited above, we expect our use of this facility to continue.

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